Abstract: The linear and nonlinear microwave properties of chemical vapor deposition (CVD) grown graphene are characterized in this work by using a co-planar waveguide (CPW) structure. The intrinsic properties of the graphene are extracted and fitted with an equivalent circuit model. The nonlinear properties of the graphene are also measured and will be used for determining the thermal properties of graphene.

Keywords: Graphene, De-embedding, Nonlinearity.

References list:

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Outline

- Introduction
- Motivation
- Test Fixture Design and Fabrication
- Experimental Characterization
- Conclusions

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Graphene Properties

- Thinnest / strongest sheet material (5 times of steel and much lighter)
- Zero band gap semiconductor: conducts as best metals and electrical properties can be modulated

Large-Area Graphene on Arbitrary Substrate

- High mobility ($\geq 100,000$ cm$^2$/Vs)
  - Ballistic conduction 100’s nm
  - High current density ($\sim 10^9$ A/cm$^2$)
- Super heat conductor ($\sim 5 \times 10^3$ W/m.K)

EM Applications

- THz (0.1-2.5 THz) and optical (188-222 THz) modulators [1,2]

- THz polarimeter (0.5-2.5 THz) and isolator at 20 GHz [3-5]

- Tunable THz absorbers [6]

- Near Infrared switch [7]

- Plasmonic cloak structure [8]

- Reconfigurable THz antenna [9, 10]

Other Applications

Graphene photodiode

Flexible LCD display

NEMS pressure sensor

100 GHz Graphene transistor demonstrated

Motivation

- Excellent electrical, mechanical and thermal properties
  - Study of graphene $\sigma$ will help towards potential EM applications
  - In addition to many free space characterizations
  - Experimental results inconsistent due to sample variations
  - $3-\omega$ method used to characterize the heat capacity of graphene

Original 3-$\omega$ structure for suspended wire

- AC signal @ω flowing through the material
- The resistance changes with the variation of temperature
- Inducing AC signal @3ω across the structure

\[ V_{3\omega} = I_\omega \times \delta R_{2\omega} \]

\[ \delta R_{2\omega} = \frac{\pi^2 I_\omega^2 RR'}{4 \omega \rho C_p LS} \]

\( C_p \): the heat capacity
\( \rho \): the mass density
\( L \): the length of sample
\( S \): the cross section of the sample
\( R \): the electric resistance
\( R' = (dR/dT) \) around room temperature
\( (= - R(\mu_c = 0)/T_0) \)

Heat capacity can be derived from 3ω measurement
• Previous work, measure long sample (e.g., nanotube) at low frequency

• In our work, measure short sample (e.g., graphene) at high frequency
  – mm-scale vs. μm-scale due to the fabrication limit
  – kHz range for long sample vs. GHz range for short sample
- CPW structure designed with $Z_0 = 50 \ \Omega$
- CVD SLG transferred onto high-$\rho$ Si
  - using the PMMA transfer method

The dimension of the CPW structure (unit: $\mu$m)

Microscope image of a fabricated graphene device
Experimental Characterization

- **Linear Characterization**
  - On-wafer measurement
  - “Open” and “Through” structures as calibration
  - Equivalent circuit model for intrinsic properties extraction

- **Nonlinear Characterization**
  - Harmonic measurement
- Measured magnitude of transmission and reflection coefficient for graphene and calibration standards:
Equivalent circuit model of the intrinsic graphene after de-embedding

- $R_c$ – the contact resistance
- $C_c$ – the contact capacitance with electrodes
- $R_{int}$ – the intrinsic resistance
- $L_k$ – the equivalent inductance of graphene
Circuit Model Fitting and Comparison with Measurement

\[ R_s = R_{int} \frac{W}{L} = R_{int} \frac{25\mu m}{10\mu m} = 682.34 \Omega/\square \]
\[ L_s = L_k \frac{W}{L} = L_k \frac{25\mu m}{10\mu m} = 0.558 nH/\square \]

<table>
<thead>
<tr>
<th>Rc [Ω]</th>
<th>Cc [pF]</th>
<th>Rint [Ω]</th>
<th>Lk [pH]</th>
</tr>
</thead>
<tbody>
<tr>
<td>49.91</td>
<td>0.193</td>
<td>272.935</td>
<td>223.079</td>
</tr>
</tbody>
</table>
Nonlinear Characterization

- Exciting the device at $f_0$ from one port
- Measuring the $3f_0$ signal at the other port

Scheme of graphene nonlinearity measurement setup

In experiment, the fundamental frequency is chosen at 1.5 GHz.
- Measured $f_0$ and $3f_0$ signals for graphene sample

Clear third harmonic for graphene sample
Measurement $3f_0$ Results

- Measured $f_0$ and $3f_0$ signals for through sample

![Graph showing through signals at $f_0$ and $3f_0$.]

No third harmonic for through sample
Conclusions

- Linear and nonlinear properties of graphene in CPW test figure are characterized
- Intrinsic linear graphene properties are extracted
  - Measured impedance (~680 Ω/sq & 0.56 nH/sq) reasonable
- Nonlinearity of graphene is investigated
  - Clear third harmonic signal seen
  - Goal is for graphene heat capacity extraction (suspended graphene is needed)
Future Work

- Investigate other nonlinear effects in graphene
- Extract the heat capacity of graphene
  - Using the extracted intrinsic circuit model parameters, together with the third harmonic results
Material Growth:

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